EVALUATION OF THEORETICAL MODELS WITH EXPERIMENTAL RESULTS OF SQUARE CONCRETE COLUMNS STRENGTHEN WITH CFRP COMPOSITES IN DIFFERENT CONFIGURATIONS

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In the past years, it has commonly seen the use of Carbon Fibers Reinforced Polymer (CFRP) externally bonded as an active technique for strengthening and repairing of deficient existing concrete columns. Accurate design models for FRP – confined concrete are required to help engineers to design suitable FRP jacket and manage the cost-effective solutions for strengthening or repairing. In this paper the evaluating of the ultimate load carrying capacities of confined square concrete columns obtained from design models are presented. Five theoretical design models, provided in codes and researchers including: ACI 440.2R-2017; FIB Bulletin-90-2019; CNR-DT 200 R1-2013; Lam and Teng model (2003) and Ouyang and Liu model (2007) have been evaluated. A comparison was made between the load carrying capacities obtained from the experimental test data and the capacities obtained from the theoretical predictions results by the mentioned codes and researchers. All three models presented by Codes showed a good agreement with experimental values except for FIB Bulletin-90-2019 that showed conservative values in two confinement cases, while Lam and Teng model showed good agreement with experimental values and Ouyang and Liu model showed conservative values with respect to the experimental values.

Keywords: *FRP, concrete column, square section, confinement, load carrying capacity*

1. Introduction

The externally bonded Fiber Reinforced Polymers (FRP) have been widely used in the strengthening of engineering concrete structures. The designers require an accurate design model for FRP confined concrete columns with square sections and suitable for direct use in design [1]. Various codes and researchers presented theoretical models for FRP-confined rectangular/square concrete columns. In 2003 Lam and Teng [2], presented a design model for rectangular columns based on recent design model, Ouyang and Liu in 2007 [3], developed a stress strain model for FRP confined rectangular columns based on the FRP-confinement weak and strong aspects. *ACI 440.2R-08 and ACI 440.2R-2017 [4 - 6]*, presented a theoretical model for non-circular confined columns based on previous studies and it was not recommended for columns with side aspect ratios (*h*/*b)* greater than 2.*CNR-DT 200 R1/2013 [5],* proposed a theoretical design model for FRP confined rectangular columns, which stating that proper confinement can only be achieved by installing FRP fibers positioned orthogonally to the member axis. FIB Bulletin-90-2019 [7], also presented a design model for rectangular columns with full and partial FRP confinement based on Lam and Teng model [2].

The aim of this paper is to evaluate the theoretical predicted capacities of square columns reported by ACI 440.2R-2017, FIB Bulletin-90-2019, CNR-DT 200 R1-2013, Lam and Teng model (2003), and Ouyang and Liu model (2007) and compare them with experimental capacities of square columns determined by the first author [8].

The details of the experimental results used for comparison with the models presented by the above mentioned codes and researchers are shown in Fig. 1 and Table 1. The specimens are labeled as CP, where C refers to Concrete and P refers to Prism then followed by the number of the specimen, except for the control specimens each one has Cnt specifies the word Control.

2. Evaluation of the theoretical models

A comparison was made between the results from experimental test and the theoretical predictions of models reported by ACI 400.2R-17, FIB Bulletin-90-19 and CNR-DT 200 R1-13, Lam and Teng model (2003) and Ouyang and Liu model (2007). All the calculation details are given bellow:

2.1 ACI 440.2R-17

According to the ACI 318R-14 the ultimate axial load capacity of unconfined concrete specimens (P_u) can be calculated from the Eq. (1) [10]

$$P_u = f_{c,cyl}\ (Ag - A_{st}) + f_y\ A_{st} \qquad (1)$$

$f_{c,cyl}$: Equivalent cylinder compressive strength $f_{c,\ cyl} = 0.8\ f_{c,\ cube}$ [9], it can be obtained from Table 1. A_g is the gross section area of the column and A_{st} is the area of the longitudinal steel. f_y is the yield strength of steel.

According to the ACI 440.2R-17 [6], the ultimate axial capacity of a nonslender, normal-

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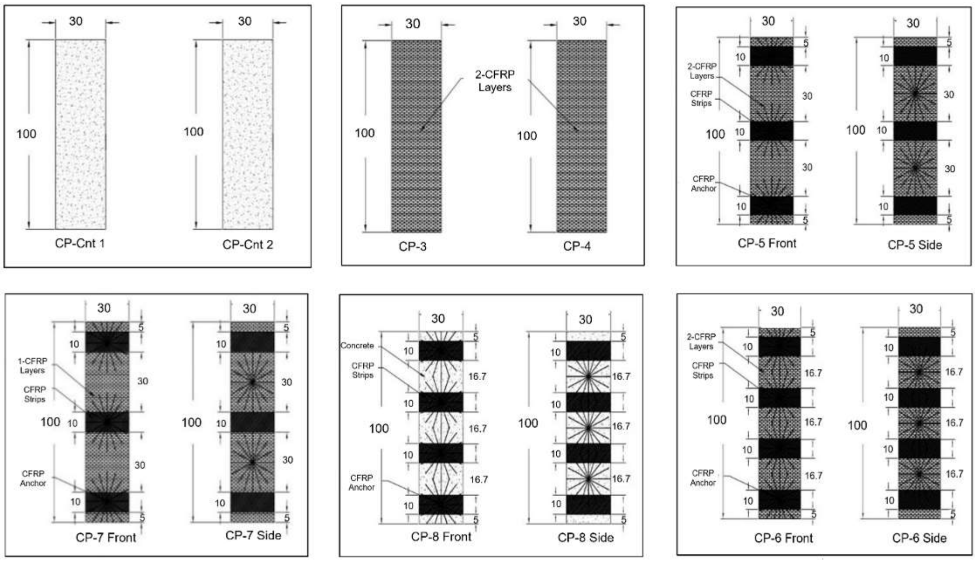

Fig. 1 - Test specimen's details. (dimensions in cm)

Table 1

Experimental results [8]

Specimen ID*	$f_{c,\,cube}$ (MPa)	$f_{c,\,cyl} = 0.8\, f_{c,\,cube}$ (MPa**)	CFRP Strengthening Details	$P_{u,\,exp}$ (KN)
CP-Cnt 1	22.5	18	-	1830
CP-Cnt 2	24.54	19.6	-	1920
CP-3	22.5	18	2 CFRP ply	2250
CP-4	24.5	19.6	2 CFRP ply	2350
CP-5	24.2	19.3	2 CFRP ply+3 CFRP strip+10 CFRP anchors	2150
CP-6	24.2	19.3	2 CFRP ply+4 CFRP strip+14 CFRP anchors	2190
CP-7	23.6	18.8	1 CFRP ply+3 CFRP strip+10 CFRP anchors	2200
CP-8	23.6	18.8	4 CFRP strip+14 CFRP anchors	2070

*: The cross sectional area of each tested column is 30x30 cm.
**: According to EN 206-1 the average compressive strength conversion factor of cubes ($f_{c,\,cube}$) to cylinder ($f_{c,\,cyl}$) is 0.8 [9].

weight concrete member confined with an FRP jacket may be calculated from Eq. (2)

$$P_u = f_{cc}\,(Ag - A_{st}) + f_y\, A_{st} \quad \ldots\ldots\ldots \quad (2)$$

According to the ACI 440.2R-17, the maximum confined concrete compressive strength, f_{cc}, and the maximum confinement pressure f_l can be calculated using (Eq. 3) and (Eq.4), respectively with the inclusion of an additional reduction factor ψ_f = 0.95

$$f_{cc} = f_{c,\,cyl} + \psi_f\, 3.3\, K_a\, f_l \quad \ldots\ldots.(3)$$

f_{cc} is the maximum concrete compressive strength of confined concrete, ψ_f is the reduction factor = 0.95 (ACI 440.2R – 17) , K_a is the shape factor, f_l is the maximum confinement pressure provided by CFRP which can be calculated from Eq. 4.

$$f_l = \frac{2\, E_f\ n\ t_f\ \varepsilon_{fe}}{D} \quad \ldots\ldots\ldots\ldots.(4)$$

E_f is the tensile modulus of elasticity of CFRP, n is the number of CFRP layers, t_f is the thickness of a layer of CFRP, ε_{fe} is the effective strain in the CFRP at failure, D is equal to the diagonal of the rectangular/square cross section (Fig. 2) as given in Eq.5.

$$D = \sqrt{b^2 + h^2} \quad \ldots\ldots.(5)$$

The effective strain in the FRP at failure, ε_{fe}, is given by

$$\varepsilon_{fe} = K_\varepsilon\ \varepsilon_{fu} \quad \ldots\ldots\ldots\ldots(6)$$

K_ε is the CFRP strain efficiency factor (ACI 440.2R-17; K_ε = 0.55)

The shape factor K_a, in (Eq. 3), depends on two parameters: the cross sectional area of effectively confined concrete area (A_e), (Fig. 2) and the side aspect ratio (h/b), as given in (Eq. 7).

$$K_a = \frac{A_e}{A_c}\left(\frac{b}{h}\right)^2 \quad \ldots\ldots\ldots\ldots\ldots(7)$$

The generally accepted theoretical approach for the definition of, A_e, assumes that the surface is delimited by four parabolas which separates the concrete area fully confined, as shown in (Fig. 2). The shape of the parabolas and the resulting effective confinement area is a function of the dimensions of the column (h and b), the radius of the corner, r_c (= 30 mm in in this work), and the longitudinal reinforcement ratio ρ_g, and can be calculated by:

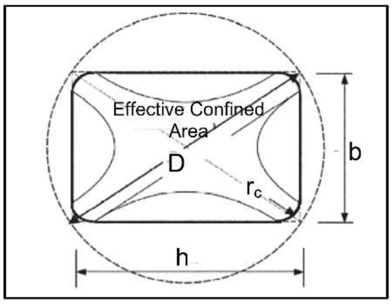

Fig. 2 - Equivalent circular cross section. [6].

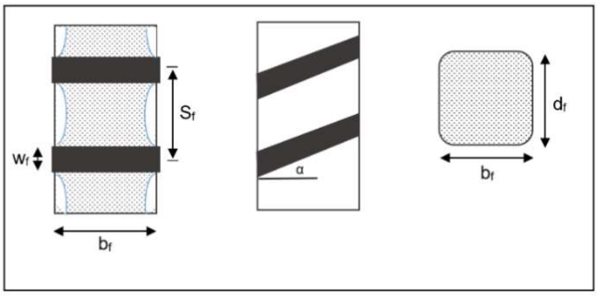

Fig. 3 - Illustration of the dimensional variables used in strengthening calculations for CFRP strips. [6].

$$\frac{A_e}{A_c}=\frac{1-\frac{\left(\frac{b}{h}\right)(h-2\,r_c)^2+\left(\frac{b}{h}\right)(b-2\,r_c)^2}{3A_g}-\rho_g}{1-\rho_g} \qquad \ldots\ldots\ldots\ldots(8)$$

According to ACI 440.2R-17 the CFRP strips contribution (partial confinement) can be calculated as shear strengthening to the column (see Fig. 3) and can be given by:

$$V_f=\frac{A_{fv}f_{fe}(\sin\alpha+\cos\alpha)d_f}{s_f} \qquad \ldots\ldots\ldots(9)$$

For rectangular/square sections

$$A_{fv}=2nt_f\,w_f \qquad \ldots\ldots\ldots\ldots\ldots(10)$$

The tensile stress in the FRP shear reinforcement at nominal strength is directly proportional to the strain that can be developed in the FRP shear reinforcement at the nominal strength.

$$f_{fe}=E_f\,\varepsilon_{fe} \qquad \ldots\ldots\ldots\ldots\ldots(11)$$

2.2 FIB Bulletin – 90 – 2019

According to FIB Bulletin – 90 – 2019, the confinement model of columns with rectangular/square cross sections with dimensions h and b (h ≥ b) (Fig. 4) is: [7]

$$\frac{f_{cd,c}}{f_{cd}}=1+3.3\left(\frac{b}{h}\right)^2\alpha_f\,\frac{2\,t_f}{D^*}\,\frac{f_{fd,h}}{f_{cd}}$$

$$\text{for }\left(\frac{b}{h}\right)^2\alpha_f\,\frac{2\,t_f}{D^*}\,\frac{f_{fd,h}}{f_{cd}}\geq 0.07 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(12)$$

$$\frac{f_{cd,c}}{f_{cd}}=1$$

$$\text{for }\left(\frac{b}{h}\right)^2\alpha_f\,\frac{2\,t_f}{D^*}\,\frac{f_{fd,h}}{f_{cd}}<0.07 \qquad \ldots\ldots\ldots\ldots\ldots\ldots(13)$$

f_{cd} is the equivalent cylinder compressive strength ($f_{c,\,cyl}$ = 0.8 $f_{c,\,cube}$) it can be obtained from Table:1. $f_{cd,c}$ is the maximum compressive strength of confined concrete, $f_{fd,h}$ is the design tensile strength of CFRP in the hoop direction, t_f = n t_0 (numbers of FRP layers multiple by the thickness of the CFRP layer), D^* is the column diagonal = $\sqrt{h^2+b^2}$, α_f is the confinement effectiveness factor, defined as the ratio of effectively confined area A_e to the total area A_g.

Note that the Eq. (12) and (13) have been obtained for h/b ≤ 2 [7].

The design tensile strength of CFRP in the hoop direction can be calculated by:

$$f_{fd,h}=E_f\,.\,\varepsilon_{fu,h} \qquad (14)$$

E_f is the tensile modulus of elasticity of CFRP, $\varepsilon_{fu,h}$ is the ultimate strain of the CFRP jacket in the hoop direction, which can be obtained from Eq. 15:

$$\varepsilon_{fu,h}=\eta_h\,.\,\varepsilon_{fu} \qquad \ldots\ldots.(15)$$

The reduction factor η_h can be taken equal to

$$\eta_h=\begin{cases}0.5\,\frac{R}{50}\left(2-\frac{R}{50}\right) & \text{for } R<50\text{mm}\\ 0.5 & \text{for } R>50\text{mm}\end{cases} \qquad \ldots\ldots\ldots(16)$$

R = corner radius

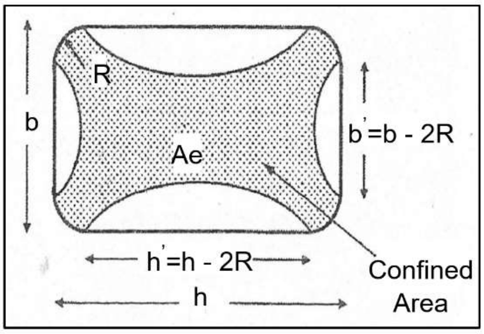

Fig. 4 - Effectively confined concrete in rectangular cross section [7].

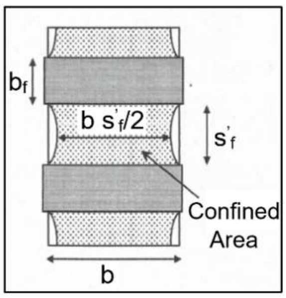

Fig. 5 - Confinement with FRP strips [7].

In the most common case of full wrapping with fibers perpendicular to the member of axis, $\alpha_f=\alpha_n$, which is given by:

$$\alpha_f=\alpha_n=1-\frac{(b-2R)^2+(h-2R)^2}{3\,b.h} \qquad \ldots\ldots\ldots..(17)$$

To account for members with partial FRP coverage (Fig. 5), α_f is obtained as

$$\alpha_f = \alpha_n \cdot \alpha_s \qquad \text{.......(18)}$$

Where

$$\alpha_s = \left[1- \frac{S_f'}{2b}\right]\left[1- \frac{S_f'}{2b}\right] \qquad \text{.........(19)}$$

S'_f is the distance between two CFRP strips.

2.3 CNR-DT 200 R1/2013

According to CNR-DT 200 R1/2013 for non-slender FRP confined members, the ultimate axial capacity can be calculated from Eq. 20: [5]

$$N_{ucc} = A_c \cdot f_{cc} + A_s \cdot f_y \qquad \text{............(20)}$$

A_c is the member cross-sectional area, f_{cc} is the ultimate compressive strength of confined concrete. The ultimate compressive strength, f_{cc}, of confined concrete can be obtained by:

$$\frac{f_{cc}}{f_c} = 1 + 2.6 \left[\frac{f_{l,eff}}{f_c}\right]^{2/3} \qquad \text{.......(21)}$$

f_c is the equivalent cylinder compressive strength ($f_{c,cyl} = 0.8\, f_{c,\,cube}$) that can be obtained from Table 1. $f_{l,eff}$ is the effective confinement lateral pressure of FRP.

The confinement is effective if $f_{l,eff} / f_{cd} > 0.05$.

The effective confinement lateral pressure $f_{l,eff}$, is a function of member cross section and FRP configuration as indicated in the following equation:

$$f_{l,eff} = K_{eff} \cdot f_l \qquad \text{........... (22)}$$

K_{eff} is a coefficient of efficiency (≤1)

The confinement lateral pressure shall be evaluated as follows:

$$f_l = \frac{1}{2} \cdot \rho_f \cdot E_f \cdot \varepsilon_{fd,rid} \qquad \text{.......(23)}$$

ρ_f is the geometric strengthening ratio as a function of section shape (circular or rectangular) and FRP configuration (continuous or discontinuous wrapping), E_f is the Young modulus of elasticity of the FRP in the direction of fibers, $\varepsilon_{fd,rid}$ is the a reduced FRP design strain.

The coefficient of efficiency, K_{eff}, can be computed by:

$$K_{eff} = K_H \cdot K_V \cdot K_\alpha \qquad \text{........(24)}$$

K_H is the coefficient of horizontal efficiency and depends on the cross-section shape. K_V is the coefficient of vertical efficiency, depending on the FRP membrane configurations.

For RC confined members with continuous FRP wrapping, it can be assumed that $K_V = 1$.

For Reinforced Concrete (RC) confined members with discontinuous FRP wrapping (Fig.6), such as FRP strips installed with a center-to-center spacing of P_f and clear spacing of P_f', reduction in the confinement effectiveness due to the diffusion of stresses (approximately at 45°) between two subsequent wrap-pings shall be considered.

Irrespective of the section shape, the coefficient of vertical efficiency, K_V, shall be determined as follows:

$$K_V = \left[1- \frac{P_f'}{2 \cdot d_{min}}\right]^2 \qquad \text{........(25)}$$

d_{min} is the minimum dimension of the cross-section.

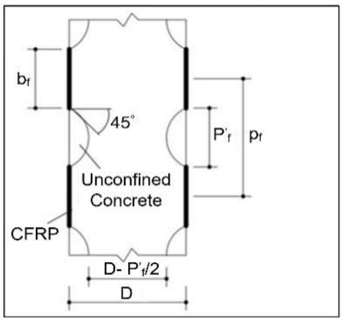

Fig. 6 - Elevation view of concrete member confined with FRP strips [5]

In case of discontinuous wrapping the net distance between strips shall satisfy the limitation $P_f' \le d_{min}/2$.

Irrespective of the section shape, the efficiency coefficient, K_α to be used when fibers are spirally installed with an angle α_f, with respect to the member cross-section, shall be expressed as follows:

$$K_\alpha = \frac{1}{1+(\tan\alpha_f)^2} \qquad \text{..........(26)}$$

The reduced FRP strain, $\varepsilon_{f,rid}$, can be computed as follows:

$$\varepsilon_{f,rid} = \min\left\{\eta_a \cdot \frac{\gamma_{fk}}{\varepsilon_f}\ ;\ 0.004\right\} \qquad \text{............(27)}$$

η_a represents the environmental conversion factor listed in Table 2 and γ_{fk} represents partial factor and it can be assumed equal to 1 [5].

Table 2

Environmental conversion factor η_a for different exposure conditions or FRP systems [5]

Exposure conditions	Type of fiber/resin	η_a
Internal	Glass/Epoxy	0.75
	Aramid/Epoxy	0.85
	Carbon/Epoxy	0.95
External	Glass/Epoxy	0.65
	Aramid/Epoxy	0.75
	Carbon/Epoxy	0.85
Aggressive environment	Glass/Epoxy	0.50
	Aramid/Epoxy	0.70
	Carbon/Epoxy	0.85

2.3.1 Square and rectangular sections

The strengthening geometric ratio, ρ_f to be used for the evaluation of the effective confinement pressure shall be calculated according to the wrapping arrangement:

(1) Discontinuous wrapping

$$\rho_f = \frac{2 \cdot t_f \cdot (b+h) \cdot b_f}{b \cdot h \cdot p_f} \quad \text{.............(28)}$$

t_f is the FRP thickness, b_f is the width of the FRP strips, p_f is the spacing between FRP strips, b and h are the cross sectional dimensions of the rectangular member (Fig. 6).

(2) Continuous wrapping

$$\rho_f = \frac{2 \cdot t_f \cdot (b+h)}{b \cdot h} \quad \text{.................(29)}$$

For rectangular cross sections, the effectively confined concrete area shown in Fig. 7.This effect depends on the values of the corner radius r_c.

For rectangular cross sections, the coefficient of horizontal efficiency, K_H, which takes into account the arch effect shall be expressed as follows (Fig. 7):

$$K_H = 1 - \frac{b'^2 + h'^2}{3 \cdot A_g} \quad \text{.............(30)}$$

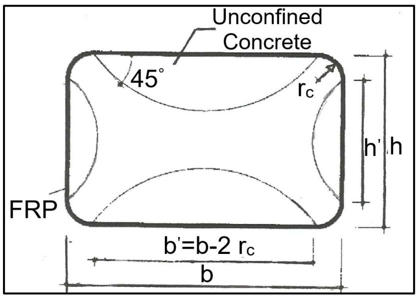

Fig. 7 - Confinement of rectangular sections

2.4 Lam and Teng model (2003)

Square columns are considered as a special case of rectangular columns with b=h [2].

$$\frac{f'_{cc}}{f'_{co}} = 1 + k_1 \frac{f_l}{f'_{co}} \quad \text{(For circular confined concrete)} \quad \text{.......................................(31)}$$

$$\frac{f'_{cc}}{f'_{co}} = 1 + k_1 k_{s1} \frac{f_l}{f'_{co}} \quad \text{(For rectangular confined concrete)} \quad \text{........................(32)}$$

f'_{cc} is the concrete strength of confined concrete, f'_{co} = Concrete strength of unconfined concrete. k_1 = 3.3 (the confinement effectiveness coefficient), k_{s1} is the shape factor. f_l is the FRP effective confining pressure produced by jacket to a rectangular cross section.

The FRP effective lateral pressure f_l is defined by:

$$f_l = \frac{2 E_{frp} \varepsilon_{h,rup} t}{D} \quad \text{..........(33)}$$

E_{frp} is the FRP modulus of elasticity, $\varepsilon_{h,rup}$ is the FRP hoop rupture strain, t is the FRP total thickness, D is the diagonal distance of the rectangular section.

The actual hoop rupture strain $\varepsilon_{h,rup}$ can be related to the ultimate tensile strain of FRP material ε_{frp} by an FRP efficiency factor k_ε calculated by:

$$\varepsilon_{h,rup} = k_\varepsilon \, \varepsilon_{frp} \quad \text{........(34)}$$

The k_ε value has been considered to vary based on the FRP material type [1]. An average value of 0.586 for k_ε has been assumed based on the analysis of previous large test database [1]. The shape factor k_{s1} for strength enhancement can be defined:

$$k_{s1} = \left(\frac{b}{h}\right)^{\alpha} \frac{A_e}{A_c} \quad \text{..............(35)}$$

Where,

$$\frac{A_e}{A_c} = 1 - \frac{\left(\frac{b}{h}\right)(h-2R_c)^2 + \left(\frac{h}{b}\right)(b-2R_c)^2}{3 A_g} \quad \text{...........(36)}$$

$\frac{A_e}{A_c}$ is the effective confinement area ratio.

For h ≥ b, the appropriate value for the exponent is α = 2.

According to this model the minimum value of FRP confinement strength is $\frac{f_l}{f'_{co}} \geq 0.07$, for which the strength improvement can be achieved.

This model has been developed for rectangular columns with fully wrapped by FRP, so in this work only columns having full confinement will have concrete strength and load carrying capacity to be calculated.

2.5 Ouyang and Liu model (2007)

This model showed that the ultimate stress f'_{cc} of FRP-confined rectangular column are mostly depending on the effective confinement ratio $(\beta' = k_s \frac{f_l}{f'_{co}})$ and the effective stiffness ratio $(\eta' = k_s \frac{E_l}{f'_{co}})$. The ultimate stress f'_{cc} with strong confinement can be given by [3]:

$$\frac{f'_{cc}}{f'_{co}} = \alpha_1 + k_1 \beta', \qquad \alpha_1 = 1.0, \quad k_1 = 3.8 \quad \text{.........................(37)}$$

When $(\eta' = k_s \frac{E_l}{f'_{co}}) \geq 12$

Similarly, based on the same analysis, the ultimate stress f'_{cc} for the weak confinement case, can be given by:

$$\frac{f'_{cc}}{f'_{co}} = \alpha_2 + k_2 \beta', \qquad \alpha_2 = 0.6, \quad k_2 = 3.1 \quad \text{..........................(38)}$$

When $(\eta' = k_s \frac{E_l}{f'_{co}}) < 12$

f'_{co} is the compressive strength of unconfined concrete cylinder, β' is the confinement ratio, η' is the stiffness ratio.

By taking into consideration the influence of the shape factor k_s, the effective confining pressure f_l and the effective confining modulus E_l can be calculated by:

$$f_l = k_s \frac{2 E_{frp} \varepsilon_{frp,rup} t_{frp}}{D} \quad \text{..................(39)}$$

$$E_l = k_s \frac{2 E_{frp} t_{frp}}{D} \quad \text{............(40)}$$

f_l is the effective confining pressure provided by the FRP, k_s is the shape factor, E_{frp} is the FRP elastic modulus, $\varepsilon_{frp,rup}$ is the effective ultimate-

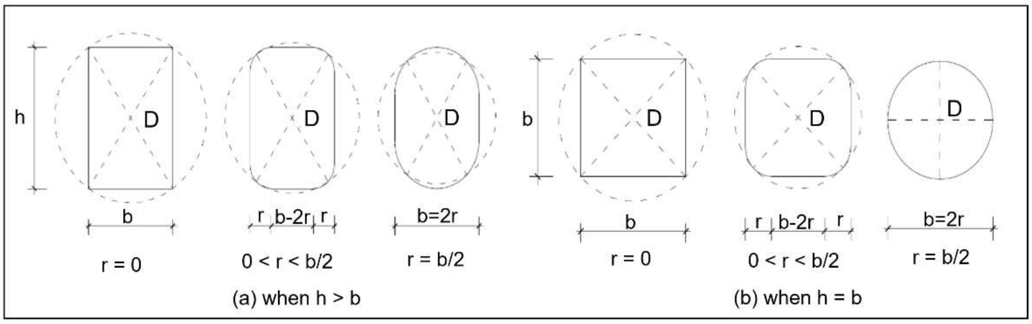

Fig. 8 - Diameter of the equivalent concrete cylinder [3].

Table 3

Comparison between the experimental and theoretical predictions provided in Codes

Specimen ID	$P_{u, exp}$ (KN)	$P_{u,ACI}$ (KN)	$P_{u, exp} / P_{u,ACI}$	$P_{u,FIB}$ (KN)	$P_{u, exp} / P_{u,FIB}$	$P_{u,CNR}$ (KN)	$P_{u, exp} / P_{u,CNR}$
CP-Cnt 1	1830	1620	1.13	1620	1.13	1620	1.13
CP-Cnt 2	1920	1764	1.08	1764	1.08	1764	1.08
CP-3	2250	2127.6	1.05	2047.5	1.09	2235.4	1.006
CP-4	2350	2272	1.03	2194.2	1.07	2397.1	0.98
CP-5	2150	2344.5	0.91	2271.6	0.94	2537.1	0.84
CP-6	2190	2394.9	0.91	2385	0.91	2585.5	0.84
CP-7	2200	2045.7	1.07	1692	1.30	2252.3	0.97
CP-8	2070	1842.3	1.12	1692	1.22	1909.8	1.08

Table 4

Comparison between the experimental and theoretical predictions provided by researchers

Specimen ID	$P_{u, exp}$ (kN)	$P_{u,Lam\ and\ Teng}$ (kN)	$P_{u, exp} / P_{u, Lam\ and\ Teng}$	$P_{u, Ouyang\ and\ Liu}$ (kN)	$P_{u, exp} / P_{u, Ouyang\ and\ Liu}$
CP-Cnt 1	1830	1620	1.13	1620	1.13
CP-Cnt 2	1920	1764	1.08	1764	1.08
CP-3	2250	2249	1.00	1599.3	1.40
CP-4	2350	2393	0.98	1681.2	1.39
CP-5	2150	2366	0.90	1666.8	1.29
CP-6	2190	2366	0.92	1666.8	1.31
CP-7	2200	2006	1.09	1329	1.65
CP-8	2070	NA	NA	NA	NA

Note: NA, means that the strengthening configuration of CP-8 was not applicable (partial confinement) to the theoretical prediction model presented by the researchers.

FRP strain rupture = 0.586 ε_{frp} (For CFRP), t_{frp} is the total thickness of the CFRP, D is the diagonal distance of the section.

Taking into account the influence of the shape factor k_s, the confinement ratio β' and the stiffness ratio η' are defined by:

$$\beta' = \frac{f_l}{f'_{co}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots..(41)$$

$$\eta' = \frac{E_l}{f'_{co}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots.(42)$$

By taking into consideration the effect of corner radius in this model, the equivalent diameter of the concrete cylinder D (Fig. 8 a) is defined by:

$$D = \sqrt{[b-(2-\sqrt{2})r]^2+[h-(2-\sqrt{2})r]^2} \qquad \ldots\ldots.(43)$$

When the shape section is square, h= b, the equivalent diameter of the concrete cylinder is the diagonal distance of the section (Fig. 8 b) defined by:

$$D = \sqrt{2}\,(b-2r)+2r \qquad \ldots\ldots.(44)$$

According to this model the shape factor k_s, is given by:

$$k_s = \frac{A_e}{A_c} = 1- \frac{\left(\frac{b}{h}\right)(h-2r)^2+\left(\frac{h}{b}\right)(b-2r)^2}{3\,A_g} \qquad \ldots\ldots.(45)$$

Where, A_e is the effective confinement area, and A_c is the column area confined by FRP.

This model has been provided for fully wrapped FRP rectangular columns; thus, in this work only columns having full confinement will have concrete strength and load carrying capacity to be calculated.

Table 3 and Table 4 show a comparison between the experimental results capacities and the theoretical predictions capacities by codes and researchers respectively.

3. Conclusions

Based on the comparative analysis between the theoretical models values and the obtained experimental values it can be concluded that:

1. All of the used models predict the ultimate load of the columns less than the experimental values of the unconfined columns and most of the confined columns as shown in Table 3 and 4.
2. The prediction values of CP-3 obtained from three codes showed good agreement with experimental values of by 5% (ACI), 9% (FIB) and 0.06% (CNR) less than the experimental values. The same was for CP-4 with values of 3% (ACI), 7% (FIB) less than the experimental and 2% (CNR) higher than the experimental. (Table 3)
3. The predicted values of CP-5 and CP-6 obtained from ACI and FIB models showed good agreement with values between (6%-9%) higher than the experimental values (Table 3), while the values obtained from CNR were not good in-agreement with experimental values by 16% higher than the experimental values.
4. The predicted values of CP-7 by ACI and CNR showed good agreement with experimental values by 7% less than the experimental value for ACI and by 3% higher than the experimental value for CNR, while the value obtained from FIB model was conservative by 30% less than the experimental value. (Table 3)
5. The predicted values of CP-8 by ACI and CNR showed good agreement with experimental values by 12% and 8% respectively less than the experimental value, while the value obtained from FIB model was conservative by 22% less than the experimental value. (Table 3)
6. The predicted values obtained by Lam and Teng model showed good agreement with the experimental values with (0%-10%) less and higher than the experimental values while the values obtained from Ouyang and Liu model showed conservative values with (29%-65%) less than the experimental values for the confined columns. (Table 4)

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